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HIGHWAY RESEARCH REPORT

OVERLAY DESIGN USING DEFLECTIONS

By

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ABSTRACT: This paper presents a state of the art of pavement
            deflection measuring experience by the California
            Division of Highways. These measurements provide
            a means of determining inplace roadway strength
            under existing conditions. The California
            Traveling Deflectometer with a test load of 15
            Kips is described as the standard deflection
            measuring device. Measurements obtained with
            this device are compared to those produced by the
            CGRA Benkelman beam rebound procedure using an
            18 Kip load.
            Correlation data is presented for follow-up
            deflection results obtained on projects reconstructed
            based on deflection studies. The various factors
            that influence a particular design selection are
            described and shown in a schematic chart.
            As a result of a recent study, a relationship
            between Benkelman beam deflection under a 15 Kip
            loading and subgrade modulus (K-value) is presented.

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A procedure is suggested, based on this criteria, to determine PCC overlay thickness design.

KEY WORDS: pavement deflection, overlay course, overlay thickness, design, instrumentation.

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SUMMARY

1. The satisfactory results of designs for overlays, based upon deflection measurements, for approximately 400 roadways, have indicated the value of pavement deflection as a tool for designing overlay thickness.

2. Experience has shown that other factors such as drainage, traffic and type of distress must also be evaluated in an overlay design.

3. A correlation was found between the California dynamic deflection and the Canadian Good Roads Association static deflection.

4. A method for determining the K-value of an existing bituminous roadway from deflection measurements has been developed. This allows for the design of a portland cement concrete overlay using existing design formulas.

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The design of roadway structural sections is
many times based on the most severe environmental condi-
tions that a particular pavement might possibly encounter
during its design life. Environmental conditions are not
consistently predictable for all geographic areas or for
all portions of any one individual project. As a result
some structural sections never experience as severe a
condition as they were designed for. On the other hand
some experience conditions which are more severe.

Because of the variation of conditions throughout a
given stretch of road the evaluation of an existing bituminous
pavement for purposes of determining structural upgrading

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should best be accomplished by an "insitu" type measure-
ment of the pavement structural strength under actual
field conditions. The California Division of Highways
and many other agencies have found that transient pave-
ment deflection measurements are a reliable means to
obtain such evaluation strength.

Pavement deflections can be used to determine
the nature and extent of reconstruction for an existing
distressed roadway. However, we have not as yet found
a reliable method for using deflections to determine when
maintenance will be required. Many roadways continue to
provide satisfactory service with only minor losses in
riding quality even though the surfacing is cracked or
exhibits distress. A pavement rating system based on
riding quality is therefore necessary to determine when
a particular roadway requires major maintenance or
complete reconstruction. The Maintenance Department of
the California Division of Highways is presently developing
such a rating system. This program, if incorporated with
pavement deflection measurements, could assist in planning
and budgeting future reconstruction of existing facilities.

State of The Art of Pavement Deflection
Measurements in California

Pavement deflection measuring experience by the

California Division of Highways dates back to 1938[1]. The
earliest device used for measuring pavement deflection was
the General Electric Travel Gage. These instruments were
installed on various California Highways as early as 1938
and on the Brighton Test Track in 1940 and later during
World War II on the Stockton Test Track. The installation
of these units required the drilling of five-inch diameter
holes through the pavement surface and the insertion of
rods to depths of up to 18 feet into the pavement section.
Through installations at various depths it was possible to
measure not only the total deflection but also the compression
contributed by each element of the structural section. It
was found that pavement deflection could be measurable up
to depths of about 21 feet. However, the majority of
deflection occurred in the top 3 feet of the structural
section. This type of gage installation was rather expen-
sive because of the time consumed in installation.

Since the use of General Electric Travel Gage
units were expensive from an installation standpoint and
relatively few measurements could be made per day, a more
sophisticated device was needed. During the WASHO Road
Test an improved version of this device, the Linear Variable
Deferential Transformer (LVDT), was used but difficulties

were encountered in maintaining calibration. As a result,
a new instrument was developed by Mr. A. C. Benkelman
during the WASHO study. This device, known as the Benkelman
beam, is manually operated and works on a simple lever arm
principle.

In 1954 the California Division of Highways
began using the Benkelman beam which greatly simplified
the task of measuring pavement deflections under wheel
loadings. An automatic deflection measuring device known
as the California Traveling Deflectometer was later
developed by the Materials and Research Department and
put into operation in 1960. A newer version was intro-
duced in 1967 and is shown on Figure 1.

The Deflectometer is based on the Benkelman beam
principle. It combines a truck-trailer unit which carries
a 15,000 pound single axle load on the rear tires and a
carriage to support probes for measuring pavement deflec-
tion under both wheels simultaneously. It is an electro-
mechanical instrument which measures pavement deflections
at 20 foot intervals while the vehicle moves steadily along
the road at 1/2 mile per hour. The deflections are
measured to the nearest 0.001 inch by means of a probe arm
resting on the pavement and are permanently recorded on
chart paper. Between 1,500 and 2,000 individual deflection

measurements are possible per day as opposed to about 300 measurements using the manually operated Benkelman beam.

Another device which is presently used by California is of commercial manufacture and is known as the Dynaflect. It is an electro-mechanical system for measuring the dynamic deflection of a roadway surface produced by an oscillatory load. The device consists of a dynamic force generator together with a motion measuring instrument, a calibration unit and five motion sensing geophones mounted on a small trailer. The trailer in a stopped position exerts a 1,000 pound peak to peak 8 cps oscillatory load onto the pavement surface through two rigid test wheels. The resulting amplitude of pavement deflection is picked up by the geophones and read as a deflection measurement on a meter located in the tow vehicle. Approximately 600 individual deflection measurements are possible per day with this unit using one sensor.

This device has been used by California on deflection research and special investigation work during the last few years. An evaluation of the Dynaflect which was reported in 1968[2] presented a correlation between this device and the Traveling Deflectometer.

Another deflection measuring system of recent commercial manufacture, which is known as the Road Rater, has been subjected to a limited amount of evaluation by the California Division of Highways. Although this evaluation was of limited scope it tends to indicate that this system has much promise. It operates on a principle similar to the Dynaflect but its operation is somewhat more flexible since the frequency of load application can be varied from 10 to 60 cps. There is a basic difference in the method of load application between the two devices. The Road Rater loading is applied through two pads attached to a steel plate whereas the Dynaflect utilizes two steel test wheels.

The Traveling Deflectometer measurement produced by a 15,000 pound single axle dual wheel load has been adopted as a standard for use by the California Division of Highways. All other measuring systems have been related to this device. Many other states and agencies utilize the Benkelman beam rebound or Canadian Good Roads Association (CGRA) procedure using an 18,000 pound single axle dual wheel load. However, we feel that the dynamic type measurement provided by the Traveling Deflectometer is more representative of the detrimental effects of repetitive wheel loading. It was found during early studies[3] that a static or standing type load deflection was generally of higher magnitude than that produced by dynamic transient type traffic loading.

From deflection data collected in 1969 on the
San Diego Experimental Base Project on Sweetwater Road
in San Diego County, Kingham presents a correlation
between the California Traveling Deflectometer and the
CGRA Benkelman beam rebound procedure.[4] This produced
a line of best fit, Y = -0.004+.52X.

Where: Y = Traveling Deflectometer deflection (Inches)
            under an 15 Kip load.

        X = CGRA Rebound deflection (Inches) under an
            18 Kip load.

The above formula is based on the first model of the
Deflectometer which has since been replaced. In terms
of our latest model Deflectometer (Figure 1) a similar
correlation with slight modification is presented on
Figure 2. This relationship produced a line of best fit,
Y = -0.002+0.52X. The coefficient of correlation, R was 0.905.
To relate this to the correlation work done by Kingham in
terms of data obtained by our first model Deflectometer, the
relationship can be explained by the equation X_1 = 1.1Y-0.0035.

Where: X_1 = Deflection in terms of the first model
             Deflectometer (Inches)

        Y = Deflection in terms of the new model
             Deflectometer (Inches)

The slight variation in the two systems is the result of
different tire sizes and pressures.

Development of Overlay Design Method

        To effectively utilize deflection measurements,
it was found necessary to relate the magnitude of pavement
deflection to pavement performance. This is not possible
through accelerated test track wheel loading since
relatively short duration testing does not permit the
average asphalt concrete surfacing to weather and harden.
To establish a reasonable tie between fatigue failure of
asphalt concrete surfacing and magnitude of transient
deflection, it was necessary to obtain deflection measure-
ments over roadways which had been in operation for
several years. This allowed the asphalt concrete sur-
facing to reach a realistic or near critical state of
hardness.

        In 1951 a comprehensive deflection research
program was initiated by the Materials and Research
Department to evaluate the above relationship as a
primary objective.

        For this study General Electric Travel Gage
units were installed on 43 projects throughout California.
The test roadways included a wide variety of pavement
structural sections since it was found earlier that
thickness of asphalt concrete surfacing was a prime

variable.   Installations were made on both cracked and
uncracked pavements.   The results of this study were
reported in 1955 in Highway Research Board Bulletin
No. 114.[3]

As a result of the above study, a 15,000 pound
single axle loading was later established as a standard
loading for use by the Materials and Research Department.
Although the allowable maximum single axle loading in
California is 18,000 pounds the 15,000 pounds more closely
represents an average for the loaded axle portion of all
trucks.   Evaluation of data from this study also suggested
maximum tolerable deflection levels for various pavement
thicknesses. These values represented the highest levels
of transient pavement deflection that a particular pavement
thickness could be subjected to during its design life without
developing fatigue cracking. The deflection criteria that was
reported in 1955 provided the basis for further study since the
roads which were investigated were mainline pavements with
relatively high traffic volumes.   To be more representative
of lower traffic situations, it was necessary to adjust
these criteria for variations in traffic volume.   This
was accomplished with fatigue tests on specimens cut
from various AC pavements and was reported by Zube and

Forsyth.[5] The present criteria for tolerable deflection
adjustment is shown on Figure 3. However, these criteria
are considered tentative because the slope lines are
based solely on laboratory surface fatigue data and have
not yet been correlated with field performance. Our
deflection experience is also limited for lightly traveled
roadways, therefore, a maximum level of tolerable deflec-
tion of 0.040 inches is suggested. Also the California
Division of Highways changed their asphalt specifications
in 1960 in hopes of producing more durable AC pavements.
This may change the tolerable limits.

California has presently underway a research
project to evaluate present deflection criteria (Figure 3)
by relating pavement performance to tolerable deflection
level, structural section, asphalt hardness properties,
and traffic loading. Deflection attenuation properties
of various roadway materials are also being investigated
on highway projects reconstructed based on California's
present overlay design method utilizing pavement deflection
measurements.[5] During the last 10 years over 400 different
roadways have been investigated to determine inplace
strength using deflection measurements. The sum total of
follow-up deflection results on projects reconstructed
subsequent to deflection investigation studies are presented

on Figure 4. Here, the basis for California's overlay
design is illustrated for various types of reconstruction.
The deflection attenuation is presented in terms of
reduction in deflection (%) versus increase in gravel
equivalent (feet). A line of best fit by regression
analysis is presented for each type of construction.
A poor correlation (R=0.208) was produced for flexible
cushion course construction (AC over AB) and was somewhat
improved (R=0.373) with the addition of cement treated
base (CTB) overlay data. However, few data points were
available for this relationship. For digout type repairs
and AC contact blankets somewhat better correlations were
determined. For example, a coefficient of correlation of
0.685 was produced for AC contact blankets and 0.746 was
determined for digout type construction. Except for thin
AC construction, the bulk of these data were obtained at
an age of 6 months or more. This allowed for initial
traffic compaction to develop. For design purposes a
single curve is presented on Figure 5 that encompasses
all types of reconstruction and provides a correlation
coefficient R of 0.745. This is the present overlay
design curve used by the California Division of Highways.
Since experience includes only a few AC contact blankets
thicker than 0.35 foot, the dashed line is used for AC

blanket repairs on a tentative basis until additional data
on thick AC overlay construction is obtained. The slope of
this line is the same as that shown for AC blankets on
Figure 4. With only minor exceptions, the performance of
our overlays have thus far been very good. On a few road-
ways, some reflection type cracking has appeared in thin
AC blankets. However, we are not aware of any fatigue type
failures such as "chicken wire" or "alligator cracking" on
overlay projects constructed according to our deflection
method. The age of these projects range from one to ten years.

Pavement Evaluation Procedure

        For corrective treatment or overlay design of a
particular roadway several factors must be considered in
addition to deflection measurements. A schematic chart
which illustrates these factors and their relationship to
other variables is presented on Figure 6.

        In arriving at a satisfactory design the following
factors are considered:

1. Cause of pavement failure.
2. Existing structural section materials.
3. Deflection magnitude of existing section.
4. Reflection cracking potential.
5. Traffic Index*
6. Tolerable deflection level.

*In the California method, Traffic Index (TI) is determined
from Equivalent Wheel Loads. It is also directly related to
gravel equivalent. For example, an increase in traffic from
10 TI to 11 TI will cause a 10% increase in required gravel
equivalent.

The first step in the evaluation process is to collect pertinent data concerning existing structural sections, unusual drainage and foundation conditions and the anticipated traffic volume. Preliminary field work then consists of selecting test sections which are representative of the various levels of pavement condition and changes in structural section. Test sections normally vary from 800 to 1000 feet in length and one or two test areas may represent a centerline mile of roadway.

Visual observations are recorded concerning type and extent of pavement distress and any vertical control features. Photographs are obtained for each test section and for all localized areas of major distress. These will aid in the overlay design and the determination as to the cause of pavement failure. Transient pavement deflections are then obtained and the mean $(\overline{X})$ and evaluated 80th percentile deflection levels are determined for each test section. These measurements are usually made in the spring or when the subgrade soils are in their most critical moisture condition. For the design based on deflections the evaluated 80th percentile deflection is used. Most areas of extreme deflection will be delineated by areas of severe distress. It is normally recommended that these areas be repaired, possibly by digouts, prior to placing the overlay.

The existence of vertical control features such as curbs and gutters may restrict overlay construction. In these situations digout type repairs may be necessary and the nature of the reconstruction would be governed by the existing structural section materials. Where no vertical controls exist, full utilization should be made of the residual strength of the existing pavement, by the placing of a contact overlay.

The extent and nature of cracking will affect the thickness required for a successful overlay. This is important in determining whether an AC blanket will add strength to the old surfacing by increasing the stiffness or whether the existing pavement is cracked to such a degree that its residual stiffness should not be considered in the design.

For some pavements, the magnitude of the existing deflection level is not a governing criteria for design. Frequently the need to eliminate potential reflection cracking from the underlying pavement establishes the AC blanket thickness. We have no set method to determine this thickness, however, a rule of thumb is generally used. This consists of recommending a new blanket thickness that is at least half the thickness of the existing asphalt

concrete pavement. For this case, the existing base must be untreated.

It should be pointed out that the deflection method for design of reconstruction is applicable only to fatigue related distress associated with excessive compression and rebound of the structural section. Evidence of instability such as permanent wheel track depressions or rutting generally indicates a weakness or thickness deficiency of a structural layer or layers. Generally, design for this latter type of failure has been by testing of samples removed from the roadbed as required by the California R-value procedure. In our experience, however, we do not have seriously rutted roads when our design criteria for deflection are satisfied.

The development of the basic criteria used for our deflection method (Figures 3 and 5) has previously been discussed. In order to illustrate the method of analysis and the procedure for determining corrective treatment a typical example is provided for a roadway with an anticipated Traffic Index of 6.5.

The existing structural section on this road consists of 0.17 foot asphalt concrete over 0.50 foot of aggregate base. Distress consists of intermittent to continuous

small "alligator" cracking which has progressed to the
point that the existing surfacing can be assumed to act
as an unbonded flexible layer. There are no curbs and
gutters and there is no evidence of rutting. Pavement
deflection measurements produced a maximum evaluated 80th
percentile level of 0.057 inches.

If there is no loss in riding quality, a seal
coat could possibly be used as an interim treatment.
However, to restore riding quality and eliminate the high
deflection condition an AC contact blanket is the most
economic repair.

A trial design would begin by selecting a 0.10
foot AC blanket. For the 6.5 Traffic Index, Figure 3
indicates 0.040 inch as the tolerable deflection. This
deflection value is used because it is considered as the
maximum deflection limit for lower trafficked roadways.

The necessary deflection reduction is:

$$\frac{0.057 \text{ inch} -0.040 \text{ inch}}{0.057 \text{ inch}} (100) = 30\%$$

It is then determined from Figure 5 that 0.25
foot of gravel equivalent is required to produce a 30
percent reduction in the existing deflection level. The
0.10 foot AC blanket is considered inadequate since 0.10
foot of AC is equal to only 0.19 foot of gravel equivalent.

A second trial design using 0.20 foot of AC is
next selected. For this thickness Figure 3 indicates a

tolerable deflection level of 0.035 inch.

The necessary deflection reduction is:

$$\frac{0.057 \text{ inch } -0.035 \text{ inch}}{0.057 \text{ inch}} (100) = 39\%$$

Figure 5 indicates that 0.40 foot of gravel
equivalent is required to produce a 39 percent reduction
in the existing deflection level. The 0.20 foot AC blanket
would provide 0.38 foot of gravel equivalent. This would
be considered sufficient.

PCC Overlays by Deflection

California's most recent contribution to the field
of deflection research, consisted of the development of a
test method for predicting the subgrade modulus (K-value)
of an existing asphalt concrete pavement from Benkelman
beam deflection measurements obtained on the pavement
surface.[6]

This criteria was developed from correlation work
done by the Canadian Good Roads Association which related
Benkelman beam deflection measurements under an 18,000
pound single axle load to the load carrying capacity of a
30 inch diameter steel bearing plate.[7] This load was
determined under a 0.5 inch plate settlement after ten
applications of load. From this relationship, a tentative
correlation curve was established in terms of a Benkelman

beam deflection under a 15,000 pound single axle load
(California's standard) and subgrade modulus (K-value) in
terms of pounds per cubic inch. This relationship is
presented on Figure 7. The tentative correlation curve
was established by first applying a factor of 0.83 to
convert the loading to California's 15,000 pound standard.
It was then necessary to convert the data to one application
of load at 0.050 inch of plate settlement to determine
K-value. A factor of 0.25 was used for the settlement
conversion and 1.2 was applied to change the data to one
application of load. With the exception of the 0.83 factor
for Benkelman loading, all other factors were obtained from
work reported by McLeod.[8,9]

The tentative correlation curve was then verified by
a minimal amount of plate bearing and Benkelman beam
measurements. This was accomplished at various test
locations on the AC hardstand areas of the Materials and
Research Laboratory and the Service and Supply Warehouse
Yard in Sacramento. A proposed design curve was then
constructed parallel to the preliminary correlation curve
and through the lowest data point. This research work
enables the Engineer to develop both flexible and rigid
overlay design alternates for existing asphalt concrete
pavements.

Portland cement concrete (PCC) overlays for distressed asphalt concrete pavements are presently selected in California on an arbitrary basis. These overlay thicknesses vary from a minimum of 0.55 foot to a maximum of 0.70 foot and in some cases may be quite conservative. Deflections now provide a basis for analysis.

The new test procedure, Test Method No. Calif. 359A, consists of first performing a deflection investigation on the existing asphalt concrete roadway as previously discussed. The subgrade modulus (K-value) is then determined based on the maximum 80th percentile deflection level using the proposed curve on Figure 7. The K-value is predicted assuming an upper limit of 600 pci. The selected K-value is then used in stress charts provided in our Planning Manual (Part 7) on Design to determine the required PCC overlay thickness. Design comparisons are now possible for AC and PCC overlays.

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Figure 1

CALIFORNIA TRAVELING DEFLECTOMETER

Figure 2

DEFLECTOMETER COMPARED TO
CGRA REBOUND DEFLECTION

Y = −0.002 + 0.52 X

R = 0.905

SWEETWATER EXPERIMENTAL
BASE PROJECT DATA (1969)

CALIFORNIA TRAVELING DEFLECTOMETER DEFLECTION (INCHES)
15,000 LB. AXLE LOAD

CGRA REBOUND DEFLECTION (INCHES)
18,000 LB. AXLE LOAD

VARIATION IN TOLERABLE DEFLECTION BASED ON A.C. FATIGUE TESTS

Figure 3

Figure 4

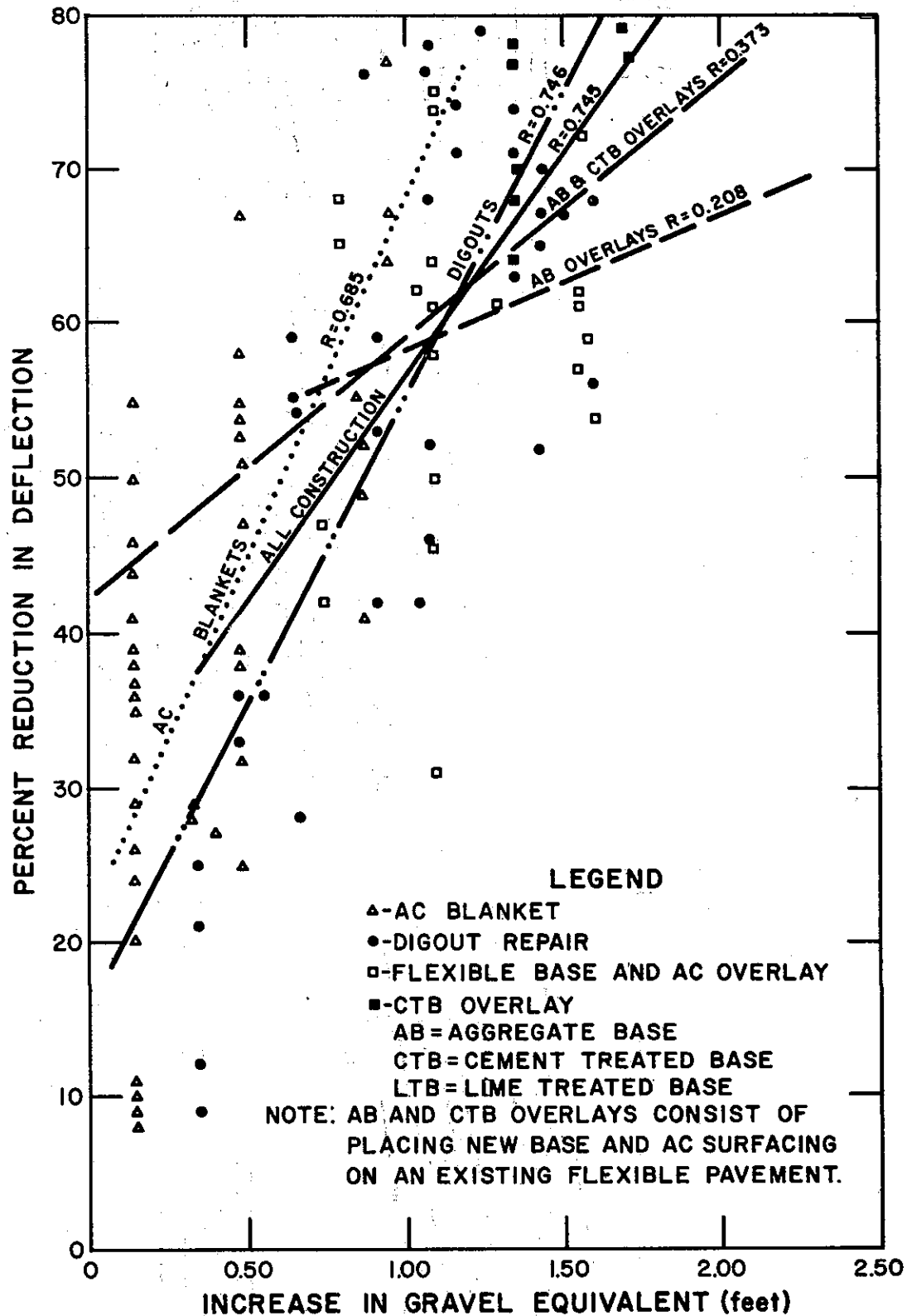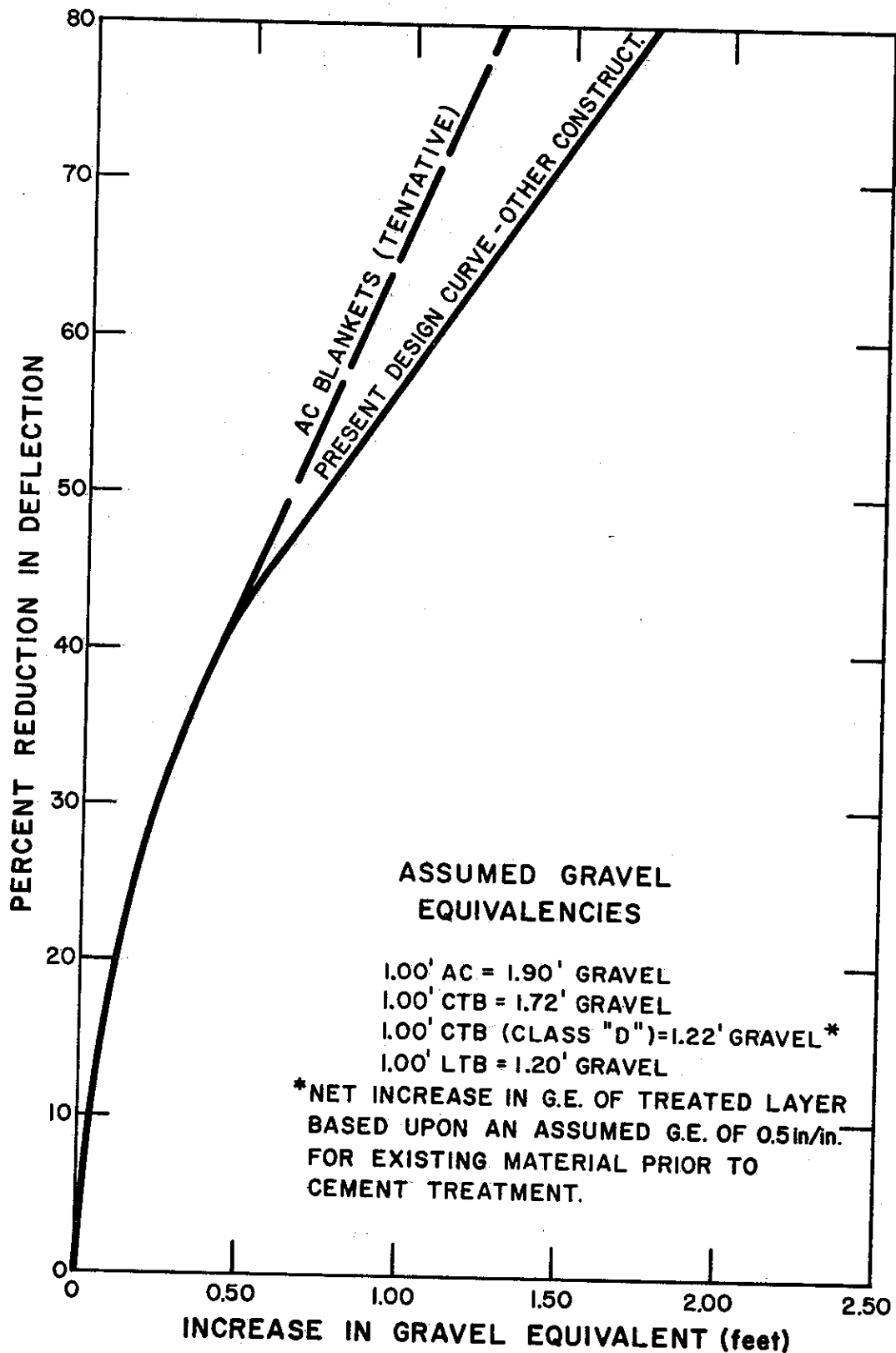REDUCTION IN DEFLECTION RESULTING
FROM PAVEMENT RECONSTRUCTION

LEGEND

△ - AC BLANKET
● - DIGOUT REPAIR
□ - FLEXIBLE BASE AND AC OVERLAY
■ - CTB OVERLAY
AB = AGGREGATE BASE
CTB = CEMENT TREATED BASE
LTB = LIME TREATED BASE
NOTE: AB AND CTB OVERLAYS CONSIST OF
PLACING NEW BASE AND AC SURFACING
ON AN EXISTING FLEXIBLE PAVEMENT.

PERCENT REDUCTION IN DEFLECTION

INCREASE IN GRAVEL EQUIVALENT (feet)

Figure 5

REDUCTION IN DEFLECTION RESULTING
FROM PAVEMENT RECONSTRUCTION

**ASSUMED GRAVEL
EQUIVALENCIES**

1.00' AC = 1.90' GRAVEL
1.00' CTB = 1.72' GRAVEL
1.00' CTB (CLASS "D")=1.22' GRAVEL*
1.00' LTB = 1.20' GRAVEL

*NET INCREASE IN G.E. OF TREATED LAYER
BASED UPON AN ASSUMED G.E. OF 0.5 in/in.
FOR EXISTING MATERIAL PRIOR TO
CEMENT TREATMENT.

AC BLANKETS (TENTATIVE)

PRESENT DESIGN CURVE - OTHER CONSTRUCT.

PERCENT REDUCTION IN DEFLECTION

INCREASE IN GRAVEL EQUIVALENT (feet)

OVERLAY DESIGN SCHEMATIC

Figure 6

Figure 7

CORRELATION BETWEEN K-VALUE
AND PAVEMENT DEFLECTION